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Ecological impacts and management challenges of non-native molluscs in China

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Rapid development in China over the past decades has been accompanied by an ongoing influx of non-native species. Many non-native mollusc species have been introduced both intentionally and unintentionally, leading to the establishment of feral populations through escapees. However, there is limited information regarding the status, threats to native biodiversity, and the contributions of these non-native molluscs to commercial breeding, the aquarium trade, and other sectors. In this study, we reviewed the impacts of introduced non-native molluscs to address these gaps. Additionally, we identified areas for future research and management recommendations. Our findings show that a total of 61 non-native mollusc species, spanning 15 orders, 23 families, and 41 genera, have been introduced into China. The primary pathway of introduction is through commercial breeding (34 species), followed by unintentional imports (20 species) and the aquarium trade (seven species). While many of these non-native molluscs are valuable as commercial breeding products and provide high nutritional value, some have caused significant negative impacts on environmental health, economic development, human health, and various aspects of aquatic and terrestrial ecosystems. Increased research on the monitoring, control, and management of non-native molluscs in China is urgently needed.

Keywords Commercial breeding, Biodiversity conservation, Ecological impacts, Human health, Invasive species

Non-native species are considered one of the most serious threats to global biodiversity and ecosystem function, inflicting significant ecological and economic loss[1,2]. Along with rapid development, a great number of non-native species are introduced continuously, especially in large countries such as Russia, Canada, the United States, Australia, South Africa, China and Brazil[3–9]. For example, there are recorded 460 non-native species in Brazil and 448 non-native species in China, respectively[8,9]. However, research about non-native species in regions such as Asia, South America, and Africa has lagged far behind that of Europe, North America and Oceania[10,11].

China is a vast country (9.6 million km^2, the third largest country in the world) with very high biodiversity (including 34,984 higher plants, 6445 vertebrates, and over 10,000 fungi) and numerous endemic species[12], but it is one of the countries most seriously threatened by invasion of non-native species[13–15]. A large number of non-native species were introduced in China for commercial breeding, the aquarium trade, horticulture, ecological restoration, for use as fertilizer, forage purposes, and other applications[13–16]. Many non-native species have established widely distributed feral populations and have caused negative impacts on native species, local ecology, human health, and the development of economy[13–18]. For example, some freshwater fishes (such as *Tilapia* species and *Gambusia affinis* (Baird & Girard, 1853)) and aquatic plants (for example *Myriophyllum aquaticum* (Vell.) Verdc. 1973 and *Cabomba caroliniana* A.Gray) have established extensive feral populations with significant negative economic and ecological impacts[19–23]. Numerousstudies has summarized the taxonomy, distribution, and impacts of non-native aquatic plants, freshwater fishes, and commercial breeding species in China[13,15,24], however there has been little taxonomic studies on non-native molluscs.

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The Mollusca Phylum is the second largest animal group of the invertebrate, and it has a high representation in diverse aquatic and terrestrial habitats[25]. Some mollusc species act as ecosystem engineers, which can significantly alter ecosystem structure and functioning[26]. Recently, many non-native mollusc species have been introduced into China and are a great threat to native biodiversity, human health, and agricultural production[14,16]. For example, apple snails (mainly *Pomacea canaliculata*) can be prey on native amphibians[27], are herbivorous and consume native macrophytes and grain[28], and alter wetland ecosystems and functions[29]. There are reports that many non-native molluscs (such as *Physella acuta*, *Pomacea canaliculate*, and *Pecten maximus*) have been introduced in China and significant impacts[30,31], however, little information exists about these non-native mollusc species.

The aims of this study are to update the inventory of non-native molluscs in China and to summarize their biological status (taxonomy, origins) and invasive capabilities (introduction pathway, ecological impacts). We hope that this study will help environment managers to better understand and control these non-native mollusc species.

Materials and methods

We conducted a comprehensive literature review that contained the following combination of words: "alien OR exotic OR non-native OR non-indigenous OR invas*" and "mollusc OR snail OR shellfish" and "China" in the title, abstract, or keywords from the WOS database (http://www.isiknoledge.com) and CNKI (http://www.cnki.net). All papers clearly introducing non-native mollusc species in China were collected and analyzed. There are a total of 763 papers have been collected and analyzed, until June 2024. Additional information was collected from selected Chinese books, such as *Alien Aquatic Plants and Animals in China*[30]. A series of field investigations about non-native species was also conducted over the past twenty years. Field surveys on mollusks were conducted across mainland China (including the Eastern Plains, Mongolian-Xinjiang Plateau, Yunnan-Guizhou Plateau, and Qinghai-Tibet Plateau) from 2008 to 2024, with a total of 500 sampling sites covering 21 provinces and municipalities in China. The primary collection tools were D net (0.25 × 2 m, with 420 μm mesh) and mussel rakes (width: 0.6 m, mesh diameter: 1 cm), supplemented by handpicking. For attached snails, a vegetation sampler was used to collect samples 1–2 times at each site, with a sampling area of 1/4 m^2. Specimens were manually picked in the field and preserved in a 10% formalin solution. All specimens were brought back to the laboratory for microscopic examination.

Results

Taxonomic diversity

We recorded a total of 61 non-native molluscs belonging to 15 orders, 23 families and 41 genera in China (Supplementary Table S1). The Haliotidae and Pectinidae were the families with the greatest number of non-native molluscs (nine species) in China, followed by the Ampullariidae with six species, and the Helicidae with five species. Each of the other families possesses less than 5 non-native molluscs.

Geographic origin

North America is the primary origin of non-native molluscs (16 species, 26.23%), followed by Asia and Europe (14 species, 22.95% respectively), South America (nine species, 14.75%), Oceania (seven species, 11.47%) and Africa (one species, 1.63%).

Introduction pathway

We identified three main introduction pathways of non-native molluscs in China (Supplementary Table S1). Commercial breeding is the primary introduced pathway (34 species, 55.73%), followed by unintentional introductions (20 species, 32.78%), and the aquarium trade ranked third (7 species, 11.47%).

Suitable habitats and distribution

China is a large country that provides a diversity of habitats, including terrestrial, freshwater and marine, for non-native species. According to our investigation, thirty-four non-native mollusc species (55.73% of total non-native molluscan species) are suitable for marine habitats. Fifteen non-native species (24.59%) are suitable for freshwater habitats. Other 12 non-native species (19.67%) are suitable for terrestrial habitats.

Information about the distribution of non-native molluscs species in China is very scarce and scattered. Based upon our field investigations and a literature review, the ranges of 46 non-native mollusc species in China are presented in Supplementary Table S1. Most non-native mollusc species are primarily distributed in South China (Fig. 1).

Time of initial introduction and first records or reports of locations in China

The rate of documented non-native mollusc introductions in China is accelerating (Fig. 2). Nearly sixty percent of non-native mollusc species were introduced after 2000. The first record of an introduced non-native mollusc species was that of *Lissachatina fulica* (Bowdich, 1822), which was imported in Fujian Province for commercial breeding in 1931[30]. It was followed by the introduction of *Bulinus truncatus* (Audouin, 1827) in 1948. Other non-native molluscs were introduced to China after the founding of the People's Republic of China (1949).

The initial site of introduction for over one third of the non-native mollusc species is unknown (23 species, 37.7%). Shandong Province has the first records of non-native molluscs (11 species, 18.03%), followed by Taiwan (7 species, 11.47%), Guangdong (6 species, 9.83%), Liaoning (5 species, 8.19%), Hong Kong (three species, 4.91%), Fujian (two species, 3.27%), and Chongqing, Jiangxi, Shanghai, and Zhejiang (one species, 1.63%). All information was presented in Supplementary Table S1.

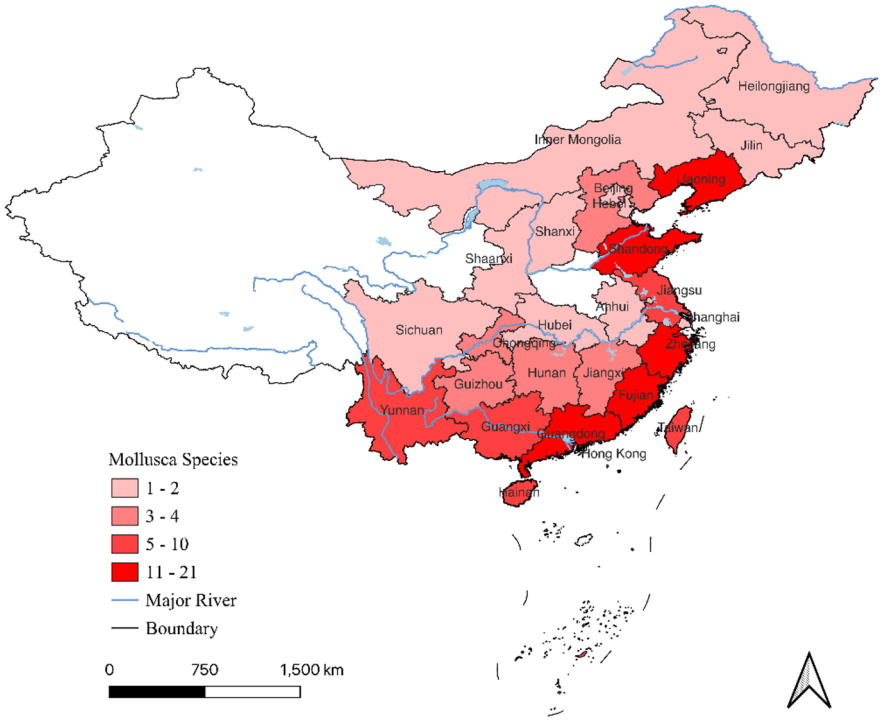

Fig. 1. Regional distribution of non-native mollusc species in China.

Ecological and economic impacts

Based on our field investigations and literature review, there are 25 non-native mollusc species that have been listed as potentially having negative ecological impacts (Supplementary Table S1). These include the impacts of their herbivory on rice and native aquatic plants (12 species), followed by competition for habitat and food and acting as intermediate parasite hosts (eight species, respectively), hybridization and genetic introgression, prey upon native species (three species in each category, respectively), and acting as occluding screens and mats covering aquaculture cages (one species). The ecological and economic impacts of non-native species are shown in Supplementary Table 1.

Discussion

Introduction pathway

Commercial breeding is one of the most important introduction pathways for aquatic non-native species[32]. Chinese commercial breeding is the fastest-growing segment in the country's food production arena, and China has become the world's leading commercial breeding producer during the past twenty years[33,34]. A great number of non-native species were introduced as additions to those farmed for food and they have improved the total production output and value[13,14,16,25]. Some non-native molluscs, such as the Atlantic Bay scallop (*Argopecten irradians* (Lamarck, 1819)), large weathervane scallop (*Mizuhopecten yessoensis* (Jay, 1857)), and giant cupped oyster (*Magallana gigas* (Thunberg, 1793)), have become particularly prominent among the farmed species in China[24]. As living standards improve, the Chinese market demand for high-value aquatic products, such as scallops and oysters has increased rapidly. Adults and juveniles of these non-native molluscs will continue to be introduced in China for improvement in the diversity of farmed food products along.

The aquarium trade has gradually become the most common introduction pathway of non-native aquatic species in China[13,15]. In addition to stores and retail outlets in large cities, many non-native aquatic plants are marketed through network platforms or pet stores[20,23,35]. Inevitably, some non-native molluscs adhere to aquatic plants and are inadvertently brought to new regions during commerce involving other live aquatic organisms[36]. For example, we observed individuals of *Pomacea* attached to the leaves of some non-native plants, such as parrot's feather (*Myriophyllum aquaticum*), fanwort (*Cabomba caroliniana*), American waterweed (*Elodea canadensis*) and large-flowered waterweed (*Egeria densa* Planchon, 1849) in some aquarium stores in Wuhan, Guangzhou, and Nanjing[37–39]. Thus, these non-native molluscs could potentially spread to the whole country by internet commerce. Some attractive shellfish such as the flame scallop (*Ctenoides scaber* (Born, 1778)) were very popular among aquarium enthusiasts because of their unique appearance and color. Some scrapers snails, such as *Planorbarius corneus* (Linnaeus, 1758), were used for the removal of attached algae by aquarium hobbyists. Finally, these non-native mollusc species were inadvertently introduced as escapees and established feral populations in natural waterbodies[30].

Unintentional introduction is another major introduction pathway for non-native molluscs in China (Supplementary Table S1). To support a rapidly developing economy, a great diversity of cargos and ores were imported into China. Some non-native species were mingled with ore shipments, wooden boxes, and sawdust,

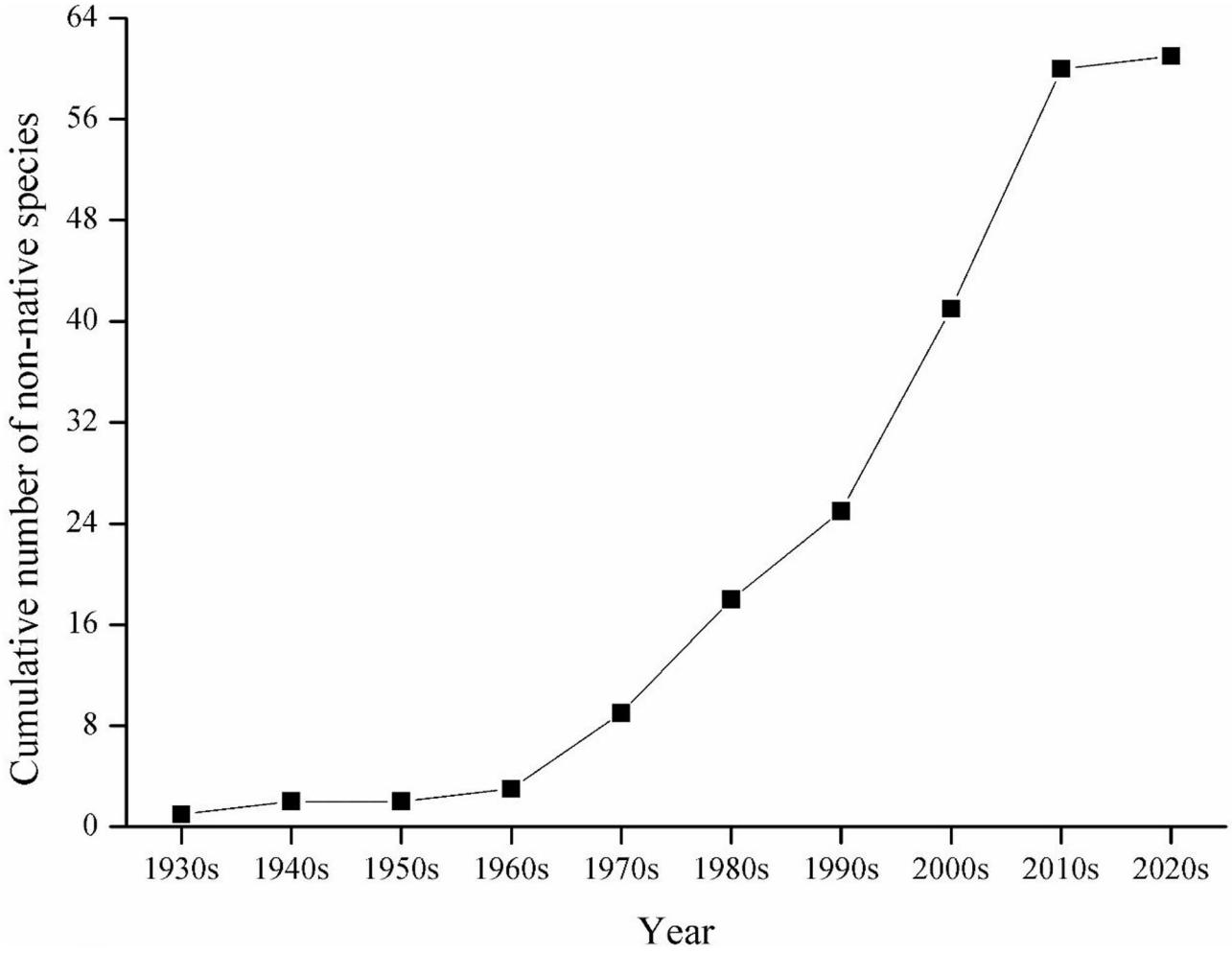

Fig. 2. The cumulative number of non-native mollusc species in China.

and thus were unintentionally brought into China[40,41]. For example, we observed that giant African snails (*Lissachatina fulica* (Bowdich, 1822)) were imported to the islands of Sanshan city mixed with sawdust and dust[42]. Because of accidental introduction, some mollusc species, such as the three band garden slug (*Ambigolimax valentianus* (A. Férussac, 1821)) and rosy wolfsnail (*Euglandina rosea* (A. Férussac, 1821)) were added to the "List of imported plant quarantine pests in People's Republic of China"[43]. It can be predicted that many more non-native molluscs will be introduced into China along with an expansion of goods transport and through Chinese international trade.

Current distribution

Overall, the number of non-native mollusc species in China's provinces has been gradually decreasing from the eastern coast to the west interior. This is because some non-native mollusc species were brought in coastal areas of China for aquaculture (Supplementary Table S). The provinces with the highest number of non-native species are Shandong and Guangdong with 21 species, respectively; followed by Fujian and Zhejiang with 16 species, respectively; Hainan and Guangxi with 11 species, respectively; Taiwan and Jiangsu with10 species, respectively. All other provinces support less than 10 species.

Ecological and economic impacts

Commercial breeding is a major and vital industry in China, which has the highest farmed fisheries production in the world[44]. Many non-native molluscs are widely used in mariculture and support rapid economic growth[14,24]. For example, the bay scallop (*Argopecten irradians*) and its subspecies Maxico bay scallop (*Argopecten irradians concentricus* (Say, 1822)), are among the most successfully cultivated non-native mollusc species. Bay scallops have been widely cultivated in the China Sea and its production there constitutes more than half of the global scallop production[45]. Another famous example is *Magallana gigas* (Thunberg, 1793), which has been grown in almost all Chinese coastal Provinces, including Liaoning, Shandong, Zhejiang, Fujian, and Guangdong. It has become one of the important commercial breeding molluscs in China. Thus, the Ministry of Agriculture (currently named the Ministry of Agriculture and Rural Affairs) of China released important commercial breeding technical specification "Pacific oyster"[46]. It is clear that these non-native molluscs are important commercial breeding

species in China and contribute significantly to local economic development and alleviating poverty and food insecurity.

Many non-native molluscs have a high potential to cause significant negative ecological and economic impacts (Supplementary Table S1). This may be because most of them are ecological engineers that substantial graze on native plant (phytoplankton and aquatic plants) or prey on native animals (including zooplankton, aquatic insects, snail, and fish), eventually causing significantly changes to native flora and fauna in a diversity of habitats, including river, lakes, and estuaries[47,48].

(1) Herbivory on crops and vegetables.

Most non-native molluscs, such as the golden apple snail and the giant African snail (*Lissachatina fulica*), are omnivores that graze on vegetables and native plants. The primary distribution of these herbivorous snails is in South China, one of China's leading grain and vegetable producing regions. For example, the farmland area invaded by golden apple snails increased rapidly from 1,290,200 hm^2 in 2011 to 1,701,100 hm^2 in 2020[49]. On the one hand, the distribution of golden apple snail has spread northward from south China (including Guangdong, Guangxi, Hainan, Fujian) to north China (like Ningxia, Hebei, Shanxi, and Shaanxi) due to global warming. On the other hand, the farmland area colonized by the golden apple snail increased quickly in South China. The farmland areas occupied by the golden apple snail in Hunan increased from 103,000 hm^2 in 2011 to 333,300 hm^2 in 2020[49]. We observed that golden apple snails damaged 43 plant species including 15 important economic agricultural crops, such as rice (*Oryza sativa* L.), lotus root (*Nelumbo nucifera* Gaertn.), and water dropwort (*Oenanthe javanica* DC.)[50]. Another famous example is that of the giant African snail, which occurs in most regions of South China and whose herbivory has decreased the quality of terrestrial agricultural vegetables produced regionally[51]. Because of the negative effects of their herbivory, the giant African snail and golden apple snail were added to the List of Alien Invasive Species in China (First Batch)[52] and to the List of Key management of Invasive Alien Species[53].

(2) Predation on native species.

As omnivores, some non-native molluscs can prey on native molluscan species. For example, *Euglandina rosea* (Férussac, 1821) feeds primarily upon snails and other molluscs[51]. It was introduced into some regions as a natural enemy of the giant African snail. However, it has caused a sharp decline in the populations of some native molluscs and even threatened these native species with extinction, jeopardizing native terrestrial ecosystems[51].

(3) Intermediate hosts of parasites.

Many non-native mollusc species, such as the giant African snail (*Lissachatina fulica*) and the ram's horn snail (*Biomphalaria straminea*), are important intermediate hosts of parasites[54,55]. A well-known example is the golden apple snail, which is an intermediate host of parasites, such as *Echinostoma revolutum*, *Gonathostoma spinigerum*, and *Angiostrongylus cantonensis*, which cause serious human diseases[54]. The most frequent cause of eosinophilic meningitis in southeast Asia and the Pacific region is angiostrongyliasis, which typically arises from eating a snail or other mollusc that hasn't been fully cooked and is carrying the *A. cantonensis* infection[56]. The first case recorded occurred in Taiwan in 1945[57], and its initial record in Guangdong Province of China mainland in 1984[58]. Since then, multiple outbreaks of eosinophilic meningitis have caught the public and government's attention in China[59]. The most serious one occurred in eastern China during 2006 with 160 sick and over 100 people hospitalized. By eating undercooked infected snails or fish containing the metacercaria of the Echinostomatide family, Echinostomiasis has infected patients in China, such as Yunnan, Fujian, Guangdong, Guangxi, Jiangsu, Anhui, Hubei, Heilongjiang, and Liaoning[60].

Biomphalaria straminea is another non-native mollusc that is of serious public health concern because it is an intermediate vector host of *Schistosoma mansoni* and can lead to schistosomiasis[61]. *B. straminea* is native to South America and was first recorded in Hong Kong in 1974[62]. It was reported in the Luohu District of Shenzhen city (a region of the China mainland bordering Hong Kong) in 1981[63]. Now, this species has become widespread in South China and has become an important intermediate host for schistosomiasis spread[64,65]. In the past twenty years, over one million Chinese workers have gone to Africa, some of whom are infected with schistosomiasis, and then returned to China[66]. This leads South China at high risk of spreading Schistosomiasis because Shenzhen city (located in the South China with a wide distribution of intermediate hosts of Schistosomiasis) is a major area of labor exporting with high population mobility and frequent international communications[67,68].

(4) Hybridization and genetic introgression.

Hybridization of native and non-native species is an important threat to native biodiversity[69]. For example, an important native aquaculture mollusc species, *Chlamys (Leochlamys) farreri* (K. H. Jones & Preston, 1904), has been displaced by two non-native species (*Mizuhopecten yessoensis* and *Argopecten irradians*) because of hybridization and genetic introgression[70]. In natural waterbodies, *Sinohyriopsis schlegelii* can hybridize with the most important Chinese native pearl culture mollusc species, such as *Hyriopsis cumingii* (Lea, 1852)[30]. It is a potential threat to China's pearl culture industry, which is the world's largest pearl cultivated producer.

(5) Competition for habitat and food.

Many non-native molluscs are introduced for commercial breeding because of their rapid growth, wide environmental tolerance, and high reproduction capability[71]. However, it is these traits that enable those non-

native molluscs to outcompete native taxa and occupy a broad range of suitable habitats and food[16]. Nine non-native mollusc species have been shown to compete for habitat and food with native mollusc species (Supplementary Table S1). *Argopecten irradians concentricus*, *Argopecten irradians*, *Pecten maximus*, *Mercenaria mercenaria*, and *Mizuhopecten yessoensis* are widely cultivated in almost all marine areas of China. Inevitably, these non-native molluscs escaped from aquaculture areas and have established wild populations that occupy large areas. Unfortunately, some of the native species, such as *Azumapecten farreri* and *Mimachlamys nobilis* have been displaced by these non-native molluscs[30]. Finally, the non-native mollusc aquaculture homogenizes intertidal soft-sediment communities for more than 20,000 km long China's coastline[72].

(6) Influences of aquaculture and human facilities.

The populations of some non-native molluscs become abundant and cover coastal cages, wharves and pipelines, which have negative impacts on mariculture, recreational sailing, and drainage systems[30]. In the past forty years, the coastal regions of China have been among the fastest growing regions in the world and a great number of human-made facilities were built along the Chinese coast[73]. For example, over 754,697 ha of coastal wetlands have been transformed for agricultural, industrial, and urban land uses[74]. Fast-growing non-native molluscs, such as the Santo Domingo falsemussel (*Mytilopsis sallei*) can cover and encase mariculture cages, causing the decline of mariculture production by decreasing light and aquatic oxygen content[30]. Some non-native molluscs foul aquaculture farming racks and ropes, and accelerate the corrosion of underwater metals, pipeline, and wharves[75]. Every year, local administrative departments spent a very large amount of money to clear notorious non-native molluscs from coastal regions of China[76]. Unfortunately, most of the cleanup and removal efforts have been unsuccessful, especially in tropical and subtropical coastal areas, where these non-native molluscs quickly re-establish their populations.

Monitoring and management

Prevention of introduction is the best choice for control of non-native species[77]. On the one hand, some new techniques, such as environmental DNA and X-ray, should be applied in animal and plant quarantines. On the other hand, some risk assessment, such as AS-ISK (Aquatic Species Invasiveness Screening Kit) and species distribution models should be conducted before the introduction of non-native species. Finally, there is an urgent need for more trained taxonomists and researchers to identify and devise management strategies for novel non-native species upon their detection[78].

China is a very large country with diverse climates and habitats. Like native species, non-native mollusc species have preferred and suitable regions and habitats that they can occupy. A first step in the compilation of an updated inventory of non-native mollusc species is to conduct more field surveys to accurately determine the distribution of problematic non-native molluscs, such as apple snails and the giant African snail. Cooperation between local governments, non-profit environmental protection organizations, and local residents is important in understanding and controlling introduced molluscs in urban and natural areas.

Eradication of non-native species is an ideal means to control the negative impacts of non-native species. Mechanical, physical, chemical and biological methods have all been conducted to control and eradicate exotics[15,79]. However, each of these approaches has some adverse consequences, such as high economic cost, adverse environmental effects, negative effects on non-targeted species, and all are limited in their effectiveness in controlling non-native species[79]. Thus, more research regarding life-history, population dynamics, and ecological impacts of non-native molluscs is urgently needed.

This study covers all regions of China, including Chinese mainland, Taiwan, Hong Kong, and Macau. However, due to funding and other constraints, we just collected limited information about the non-native species in Taiwan, Hong Kong and Macau regions. Therefore, we hope to increase collaboration with scholars from these three regions in the future so that we can better study and manage non-native species in China.

Data availability

Data is provided within the manuscript or supplementary information files.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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